



Preliminary Study on Safety Performance Evaluation of Petrochemical Plant Layout

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Abstract

Due to the gathering of hazard materials, petrochemical plant always has extrusive fire and explosion risk. Unreasonable plant layout could bring high accident frequency, secondary accident possibility, and immense financial loss. The expected characters of a *safe* layout were analysed at first in this work, and then four key metrics were proposed to evaluate the safety performance of the layout. These four metrics are *accident triggered likelihood degree*, *improper degree of domino risk*, *improper degree of facility damage risk/ human injury risk* and *evacuation difficulty degree*. Based on the character analysis, the mathematical representations of the four metrics were also preliminarily analyzed.

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1. Introduction

Fire, explosion and poisoning hazards are of high risks in petrochemical industry, which can often lead to serious accident consequences and bad social influence^[1]. The plant layout is one important factor that contributes to the accident probability and accident consequence. It can be known from historical cases that the unreasonable layout may increase the accident probability, enlarge the potential accident financial loss and even cause the domino effect that further enlarges the accident scale and accident consequence^[2-3]. The safety evaluation technology of plant layout takes the responsibility of confirming the safety performance of a layout scheme. It can be used to choose the best one from several schemes. Unfortunately, there is not a good technology yet. In the perspective of inherently safe, Faisal Khan proposed a guide words based index method to evaluate the safety performance of the plant layout. In the method, many influence factors such as fire & explosion hazard, domino effect and safety protection measures are taken into consideration, and ways to determine the value of each index are also provided^[4-5]. However, the method is difficult to be carried out because the determination of many indexes is subjectivity. In China, the relevant research is almost blank. However, the government has paid much attention to the safety performance of plant layout. For example, the safety analysis of layout is requested as an essential part of the safety pre-assessment report. But due to the lack of effective theory and technology, current plant layout safety analysis has been instead of criterions checking. The method is helpless to those analyses of layout schemes which have met the criterions terms. In this work, the main influence factors of layout safety and their mathematical representation were studied as the bases of a systematic evaluation technology.

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2. Impact analysis of layout to the enterprise safety

The layout can affect the safe operation of enterprises in many ways. Generally, plant layout of good safety performance should have the following characteristics:

2.1. Low accident probability

Unreasonable layout could increase the probability of serious accident, such as fire and explosion. The main concern here is how to arrange the position of ignition source unit relative to flammable gas release source unit. The flammable gas release source unit means facility or position which could release flammable gas, and the ignition source unit means facility that contains any kinds of ignition energy, such as fired heater, non-explosion proof electric apparatus and so on. Reasonable layout can consider the process requirement and environmental impact factors, and arrange reasonable positions for all release source units and ignition source units. The ignition sources are always arranged at the position with low coverage risk of flammable gas, so as to reduce the probability of gas explosion.

2.2. Low domino risk

During the factory planning process, for the benefits of easy management and effective utilization of resources, some high-risk equipment are usually concentrated into one area, e.g. tank farm. In these areas, domino risk is very outstanding. Rational layout needs reasonable design of relative position and mutual distance of these facilities that can deduce the domino risk to lowest.

2.3. Low personnel and economic losses

In a plant, some units which are of high-personnel density, high-economy density or of high process importance, such as the office building, central control room, laboratory, fire station, telecommunications station etc., are the key protection facilities and are expected to be least or last units to be damaged in the plant. Reasonable layout shall select the areas with lowest risk as the location of these units by reference to the risk field of the whole plant zone, so that to lower the personnel and economic losses under accident conditions.

2.4. Escape convenience under emergency condition

Once fatal accident occurs, in order to prevent the expansion and worsen of accident, personnel in the plant must be promptly evacuated and transferred to safety belt, and reasonable layout can guarantee a fast and safe evacuation. To make it possible, a rational evacuation route should been set as short as possible for each high-personnel density unit, and one essential rule is that the evacuation route should not pass through the high risk regions.

3. safety performance metrics and mathematical representation

Based on above analysis, four metrics were proposed to evaluate the safety performance of the layout. The mathematical representations of the four metrics were also preliminary studied.

3.1. Accident triggered likelihood degree

Accident triggered likelihood degree is used to evaluate the safety rationality of the relative position relationship of ignition source unit and release source unit. From analysis, it can be known that the probability of fire and explosion will be lower if the following principles can be fulfilled.

- (1) The ignition source unit should be located at the upwind direction of all release source units (the less the amount of release source that located at the upwind direction, the better the safety performance);
- (2) Keep ignition source unit away from release resource unit (the larger the distance between ignition source unit and release source unit, the better the safety performance);
- (3) As gas diffusion under wind direction is easier than under crosswind direction, keep upwind release source far away from the due upwind direction of ignition source (the smaller θ in Figure 1, the better the safety performance).

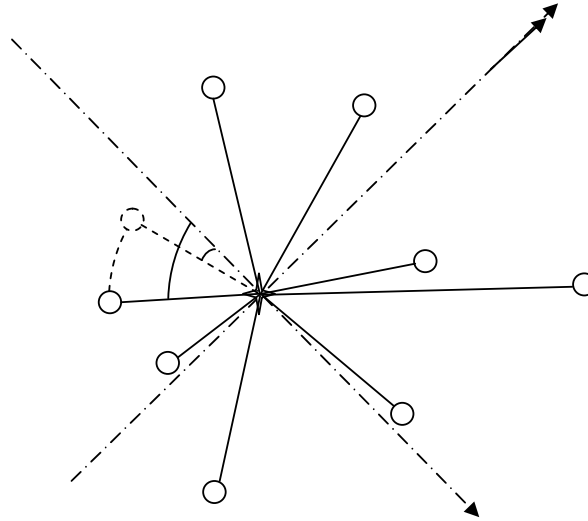


Figure 1 the Relationship diagram of ignition source and release source

According to above analyses and considering the applicability under special conditions, a mathematical expression (Equation 1) was put forward to represent the *Accident triggered likelihood degree*. The equation shows that the smaller the number m of the upwind release source and the sum of θ (the minimum angle between release source and horizontal axis), the smaller the *Accident triggered likelihood degree* of current ignition source. In addition, the larger the sum of distances between release source and ignition source, the smaller the *Accident triggered likelihood degree* of current ignition source.

$$R_{s,k} = \frac{n \cdot (m + 1) \cdot \left(1 + \sum_{j=1}^m \theta_j\right)}{\sum_{i=1}^n |S_i \rightarrow o_k|} \quad (1)$$

Where, $R_{s,k}$ —the *Accident triggered likelihood degree* of the k^{th} ignition source, dimensionless;

n —the number of release source, number;

m —the number of upwind release source, number;

θ_j —the minimum angle between the j^{th} release source and horizontal axis, radian;

$|S_i \rightarrow o_k|$ —the distance between the i^{th} release source and the k^{th} ignition source, m;

As there are several ignition sources in a plant, the *Accident triggered likelihood degree* of every ignition source should be calculated, and the sum of all the number is the *Accident triggered likelihood degree* of the whole plant. If the value is small, it indicates that the risk of fire and explosion accident triggered by ignition source unit is low; otherwise the risk is high.

$$R_s = \sum_{k=1}^t \frac{n \cdot (m + 1) \cdot \left(1 + \sum_{j=1}^m \theta_j\right)}{\sum_{i=1}^n |S_i \rightarrow o_k|} \quad (2)$$

Where, R_s —the *Accident triggered likelihood degree* of the whole plant, dimensionless.

3.2. Improper degree of domino effect

The *Improper degree of domino effect* is to evaluate the safety rationality of the relative position relationship of vulnerable facilities. The analysis of this metric is based on a hypothesis that facility with high primary accident risk is also likely to be destroyed by blast wave or heat radiation (high domino risk). With the hypothesis, from analysis, it can be known that the probability of domino effect will be lower if the following two principles can be fulfilled.

- (1) Facility with high primary accident risk/ high domino risk shall be located at the edge of the zone (keep maximum distance from other vulnerable facilities for domino risk reducing purpose). Figure 2 shows the layout's influence to domino risk.
- (2) The area of the vulnerable facilities concentration zone should be as large as possible.

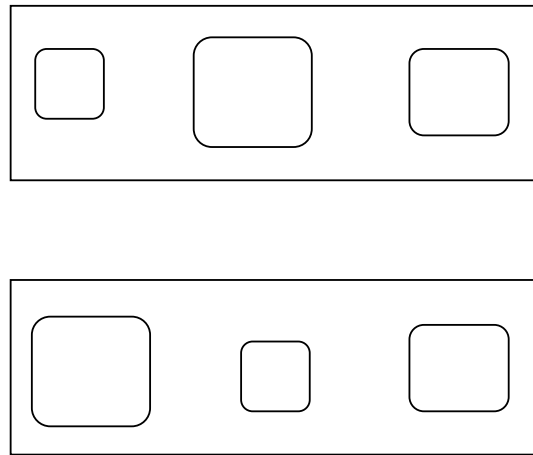


Figure 2 Layout's influence to domino risk

According to above analyses and considering the applicability under special conditions, a mathematical expression (Equation 3) was put forward to represent the *improper degree of domino effect*. From the equation, it can be known that if facilities' ranking number of primary accident risk matches well with the ranking number of 'edge degree', the *improper degree of domino effect* will be low, and the bigger the area of the vulnerable facilities concentration zone, the lower the *improper degree of domino effect*.

$$R_d = \frac{1 + \sum_{i=1}^n |i - N_i|}{n \cdot S} \quad (3)$$

Where, R_d —*Improper degree of domino effect*, dimensionless;

n —the number of vulnerable facilities, number;

i —the primary accident risk rankings number of vulnerable facility, number;

N_i —the 'edge degree' ranking number of facility i , number;

S —the area of the vulnerable facilities concentration zone, m^2 .

According to the above analysis, the process to determine the *improper degree of domino effect* is as below:

- (1) Evaluate the primary accident risk/ domino risk for every vulnerable facility in the concentration zone, and attach a ranking number for every facility;
- (2) Calculate the sum of the distances to other facilities for every facility, and attach a ranking number N_i for every facility;
- (3) Bring the i and N_i that calculated by step (1) and step (2) into the equation (3) to get the *Improper degree of domino effect*.

3.3. Improper degree of facility damage risk/ human injury risk

The *improper degree of facility damage risk/ human injury risk* is to evaluate the safety rationality of the locations of the high-personnel density, high-economy density facilities. From analysis, it can be known that:

- (1) Facilities' locations should be determined by their importance. If a more important facility, e.g. high-personal density facility, was located at a position with high damage risk, and meanwhile a less important facility, e.g. high-personal density facility, occupied a position with lower damage risk, it means the current layout is unreasonable, and a better layout can be gotten by further optimal design.
- (2) The lower the damage risk of the locations of high-personal density and high-economic density facilities, the better

the safety performance is.

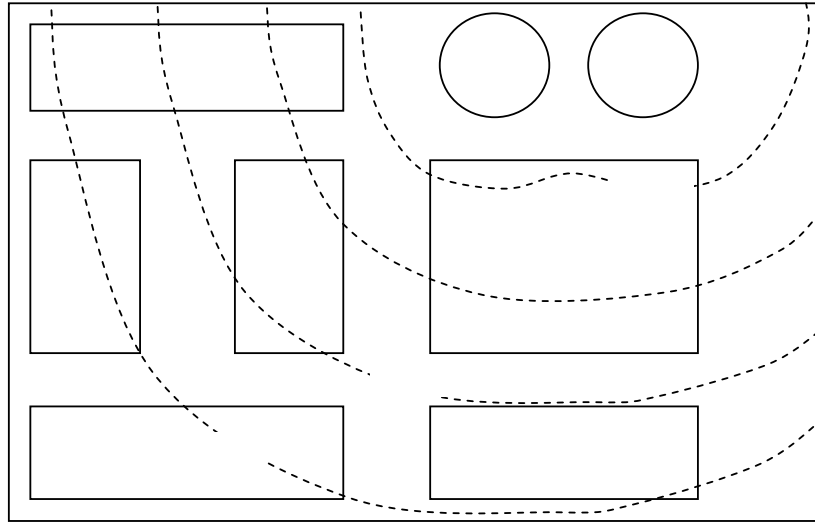


Figure 3 Unreasonable locations for high-personnel density and high-economy density facilities

Note: a/b , a is the importance rankings number of the facility, and b is the damage risk ranking number of the facility

According to above analyses and considering the applicability under special conditions, a mathematical expression (Equation 4) was put forward to represent the *improper degree of facility damage risk/ human injury risk*. From the equation, it can be known that if facilities' ranking number of importance matches well with the ranking number of the damage risk (can be replaced by the individual risk), the *improper degree of facility damage risk/ human injury risk* will be low, and the lower the damage risk, the lower the *improper degree of facility damage risk/ human injury risk*.

$$R_p = \frac{\left(1 + \sum_{i=1}^n |i - N_i|\right) \cdot \sum_{i=1}^n p_i}{n} \quad (4)$$

Where, R_p —the *improper degree of facility damage risk/ human injury risk*, dimensionless;

n —the number of the importance facilities, number;

i —the importance rankings number of the facility, number;

N_i —the damage risk ranking number of facility i , number;

p_i —the damage risk of facility i .

According to the above analysis, the process to determine the *improper degree of facility damage risk/ human injury risk* is as below:

- (1) Evaluate the importance for every facility according to the personnel density and economy density, and attach a ranking number for every facility;
- (2) Calculate the damage risk(individual risk) for every facility, and attach a ranking number N_i for every facility;
- (3) Bring the i and N_i that calculated by step (1) and step (2) into the equation (4) to get the *improper degree of facility damage risk/ human injury risk*.

3.4. Evacuation difficulty degree

The *Evacuation difficulty degree* is to evaluate the safety rationality of evacuation routes. From analysis, it can be known that:

- (1) The shorter the evacuation route, the better the safety performance is;
- (2) The evacuation route should not pass through the high risk regions. As figure 4 shows, if the gate is set at the position G, when people evacuating follow the route, he has to pass through the high risk region first. But if the gate is set at the position G', the evacuation route is safer.

According to above analyses, a mathematical expression (Equation 5) was put forward to represent the *Evacuation*

difficulty degree. From the equation, it can be known that the two main factors of the *Evacuation difficulty degree* are the route length that passes through the high risk region (L_{above}) and the backward risk span ($p_{max}-p$).

$$R_t = \frac{\sum_{i=1}^n (p_{i,max} - p_i) \cdot L_{i,above}}{n} \quad (5)$$

Where, R_t —*Evacuation difficulty degree*, dimensionless;

n —the number of the crowded places, number;

p_i —the individual risk at the position of crowd place i ;

$p_{i,max}$ —the maximum individual risk value of the whole evacuation route;

$L_{i,above}$ —the route length that passes through the high risk region, m.

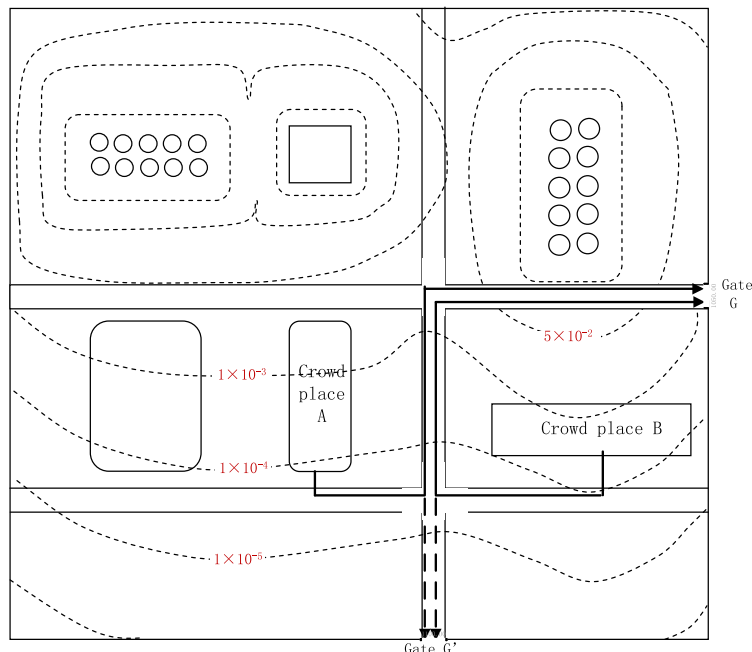


Figure 4 The evacuation route in the risk field

4. Conclusions and prospect

The work put forward four metrics to evaluate the safety performance of a layout. These four metrics are *improper degree of facility damage risk/ human injury risk*, *improper degree of domino risk*, *accident triggered likelihood degree* and *evacuation convenience degree*. The mathematical representations of the four metrics were also preliminarily analyzed. The metrics proposed are in the preliminary discussion stage and the mathematics representations expressions need further improvement. Furthermore, to build a systematic evaluation method, more research work should be done on metric grading and comprehensive evaluation of four metrics and so on.

Acknowledgements

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